

HIGH VOLTAGE PROPERTIES OF INSULATING MATERIALS MEASURED IN THE ULTRA WIDEBAND *

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Abstract

Numerous dielectrics have been developed for various high-voltage high-power microwave applications. The primary goals for HPM insulation are to provide adequate insulation over the lifetime of the device, provide high dielectric strength at low volume and weight, and function with minimal maintenance and ancillary components. Current testing methods for dielectric materials are antiquated processes developed around the 60 Hz machine world and prove inadequate for high-voltage high-frequencies pulses. We report the development of an insulation processing and testing system for engineering and verifying solid and resin/epoxy dielectric insulators for high-voltage radar systems in the pulse regime. The system tests material properties at high voltages over a frequency range of 100 MHz to 10 GHz. A second procedure characterizes breakdown and partial discharge thresholds. The system targets in-situ inspection of the dielectric liner within an HPM generator housing to verify insulator integrity prior to deployment.

I. INTRODUCTION

Current and future HPM systems rely on advancements in dielectric materials due to continued increase of HV in smaller volumes. Performance characteristics in dielectric strength and thermal conductivity are important for mobile or airborne systems, since higher dielectric strengths lead to smaller containment vessels and increased thermal conductivity reduces heat removal requirements.

High frequency radiation sources, such as x-band radar systems, typically exhibit extremely compact geometries that result in high electric field strengths between components and ground planes. Inadequate characterization of insulating materials reduces the range of voltage levels to operation at known *safe* levels, because operating margins in overstressed conditions are not well documented. Currently, safe operating parameters are determined using testing procedures employed by the power industry for many decades.

Development of HPM technologies for mobile terrestrial and airborne systems is well underway. Such

systems may operate with source voltages of several hundred kV. Typically, these HV sources use electronegative gases or liquids as insulating mediums, and include transformer oil, *Flourinert*, and sulfur-hexafluoride (SF₆). These media are plagued with a high overhead in filtering and flowing systems, but offer the advantage of self-healing insulation. Systems employing solid dielectrics may result in reduced volumes and higher operating voltages, but are vulnerable to catastrophic failure due to the lack of understanding of their physical properties at operating points in applied voltage and frequency for short pulses. Thus, the gains in operating parameters are nominal since safety margins are chosen very conservatively.

We present results of a research effort designed to incorporate engineered solid dielectric materials into RF and HPM system design with a higher degree of confidence of the material meeting electrical and thermal performance specifications. The initial phase of the effort concentrated on establishing testing procedures for existing materials, with measurement of dielectric constant, loss, partial discharge and breakdown voltage, and dielectric strength. We have tested a variety of materials with ultra wideband (UWB) frequencies (100 MHz to more than 2 GHz) and extreme voltage levels in excess of 200 kV in the pulse regime and report the results in this letter. Future efforts will apply this methodology and the information gleaned to compliment the design of customized materials in HV systems. Material processing techniques and post-process test design are in current development at APELC to identify material weaknesses, e.g. partial discharge and structural flaws, in order to ensure insulator viability prior to deployment.

II. BACKGROUND

In this section we give background information and the analysis equations used in the characterization of the dielectric materials identified in Table 1. These materials were selected because of their use as microwave insulators. The primary goal of first phase of this effort is

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14. ABSTRACT Numerous dielectrics have been developed for various high-voltage high-power microwave applications. The primary goals for HPM insulation are to provide adequate insulation over the lifetime of the device, provide high dielectric strength at low volume and weight, and function with minimal maintenance and ancillary components. Current testing methods for dielectric materials are antiquated processes developed around the 60 Hz machine world and prove inadequate for high-voltage highfrequencies pulses. We report the development of an insulation processing and testing system for engineering and verifying solid and resin/epoxy dielectric insulators for high-voltage radar systems in the pulse regime. The system tests material properties at high voltages over a frequency range of 100 MHz to 10 GHz. A second procedure characterizes breakdown and partial discharge thresholds. The system targets in-situ inspection of the dielectric liner within an HPM generator housing to verify insulator integrity prior to deployment.				
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to experimentally characterize dielectric properties and quantify differences with vendor specifications.

Two geometries were constructed for the tests. One was a standard stripline on dielectric substrate; the second was a ‘hockey puck’ configuration with two electrodes embedded in the dielectric substrate to form a parallel plate geometry with a gap spacing of 0.1 inch.

A. Calculation of Relative Permittivity

Permittivity was measured using the stripline geometry. The relative permittivity is calculated from standard transmission line theory. Stripline impedance is related to reflection coefficient Γ

$$Z_L = \frac{1 + \Gamma}{1 - \Gamma} Z_o \text{ ohm.} \quad (1)$$

The relation between the impedance of a stripline transmission line is and the relative permittivity ϵ_r is given by

$$Z_L = \frac{377}{\sqrt{\epsilon_r} [(w/h) + 2]} \text{ ohm} \quad (2)$$

where w is the strip width, h is the height above the ground plane, and it is assumed that $w > h$ [2]. Equation (2) was used to fabricate striplines of 50Ω using the vendor specified value for ϵ_r at 1 MHz.

The frequency dependence of the relative permittivity may be determined with scattering parameter s_{11}

$$\epsilon_r = \frac{377}{50} \cdot \left(\frac{1 - s_{11}}{1 + s_{11}} \right) \cdot \frac{1}{[(w/h) + 2]} \quad (3)$$

where $s_{11}(f)$ is determined by a frequency sweep in the experiment.

B. Calculation of propagation delay

Time delay τ is defined as the difference between the pulse propagation time through cable and the pulse propagation time through the stripline and cable combination. The time delay is given by

$$\tau = \frac{L}{v_{prop}} \text{ sec} \quad (4)$$

where L is the length of the stripline and v_{prop} is the propagation speed. The propagation speed through the stripline in the absence of dielectric substrate is a known quantity c . Hence, by

$$n = \frac{c}{v_{prop}} = \sqrt{\epsilon_r \mu_r} \quad (5)$$

we may calculate refractive index n thence the relative permittivity, since $\mu_r = 1$ for a nonmagnetic material [2].

C. Calculation of dissipation and loss

The dissipation factor D is defined in terms of the loss tangent

$$D = \tan(\delta) \quad (6)$$

where for permittivity $\epsilon = \text{Re}(\epsilon) - j \cdot \text{Im}(\epsilon)$, δ is given by

$$\delta = \text{Im}(\epsilon)/\text{Re}(\epsilon) \quad (7)$$

after [2]. D is typically quoted in vendor data for 1 MHz. In the experiment, the frequency dependent loss is determined by measurement of s-parameters s_{11} and s_{21} over swept frequency

$$\alpha = \frac{1 - s_{11}^2}{s_{21}^2} \quad (8)$$

where α represents $\text{Im}(\epsilon)$ for measured data [3]. In the results section, we compare α to vendor $\text{Im}(\epsilon)$.

III. METHODOLOGY

In this section we discuss the experimental procedures employed in characterization of the dielectric materials.

A. Measurement of dielectric constant

For measurement of the dielectric constant for the dielectric substrate in the stripline geometry, a low voltage signal from a Stanford DG535 pulse generator through a pulse sharpening diode provided a test pulse with a maximum frequency of 3.5 GHz. The propagation time for the pulse to traverse the test cable was measured as a reference. The propagation time for the pulse to traverse cable and stripline combination was measured in order to quantify propagation delay τ , and used to calculate the dielectric constant at 3.5 GHz listed in Table 1.

B. Measurement of Loss

To measure the loss of the dielectric substrate in the stripline geometry, a frequency sweep was performed using the Agilent E8362B Vector Network Analyzer. The network analyzer determines s-parameters s_{11} and s_{21} for frequencies ranging from 100 MHz to 10 GHz. Permittivity components $\text{Im}(\epsilon)$ and $\text{Re}(\epsilon)$ are then calculated by use of (3) and (8).

C. Measurement of Partial Discharge and Break down voltages

The configuration for this experiment is shown in figure 1. An APELC Marx generator MG15-3C-940PF provided pulsed voltages from 36 kV to 260 kV of 200 ps rise time and full duration of 20 ns to the material sample mounted inside vacuum chamber. The pulse enters the chamber and propagates a coax-to-planar transition to excite the sample. The pulse propagates a planar-to-coax transition after which it propagates through RG-220 cable to the matched load. An inline current viewing resistor (CVR) monitors the pulse on load cable. A second CVR monitors the discharge current through sample.

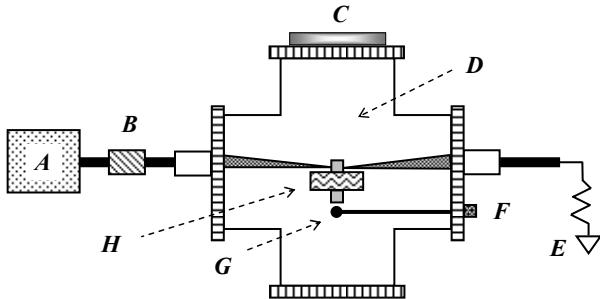


Figure 1. Experimental set up for partial discharge and breakdown voltage testing. APELc Marx generator model MG15-3C-940PF (**A**), cable CVR (**B**), acrylic window (**C**), evacuated volume (**D**), matched load resistor (**E**), BNC feed through (**F**), discharge monitor CVR (**G**), and hockey puck sample (**H**).

IV. RESULTS

From the UWB excitation, we selected 3.5 GHz as a bench mark in calculations to demonstrate difference in permittivity. This value is compared to values listed at 1 MHz. Materials used in the experiment and results are summarized in Table 1, 2 and 3.

Table 1. Measured dielectric constant vs. vendor specification.

Material	Measured 3.5 GHz	Vendor spec 1MHz
Epoxy 815c/3140	2.287	3.80
VRI 704	2.516	2.00
Dolphon	1.763	15.00
Conathane	2.265	2.80
Ultem 1000	2.879	3.15
Rexolite	2.069	2.53
Udel	2.755	4.10
Pomalux	2.755	3.80
Zelux-W	2.400	2.90
Zelux SD-P	9.830	2.50
Fluorosint	3.240	2.85

V. DISCUSSION

Measurements in table 1 demonstrate differences between vendor data collected with low frequency CW excitations and data collected for high frequency HV pulses. A frequency sweep reveals the frequency dependence of each material's permittivity and establishes that experimental data over this range is significantly at odds with vendor data.

One case in which $Re(\epsilon)$ is significantly lower than vendor data is shown in figure 2 for the *Dolphon* material. This figure illustrates the possibility of failure of the insulation (i.e. punch through) for a HV system while operated at high frequency with the volumetric

requirements of the insulator design based upon vendor dielectric strength specifications.

Table 2. Measured $Im(\epsilon)$ vs. vendor specification.

Material	Measured 3.5 GHz	Vendor spec 1 MHz
Epoxy 815c/3140	3.73	--
VRI 704	4.00	--
Dolphon	1.10E+07	--
Conathane	4.81E+01	2.80E-02
Ultem	1.72	4.09E-03
Rexolite	1.35	3.04E-04
Udel	2.19	2.46E-02
Pomalux	6.82	1.90E-02
Zelux-W	2.39	2.90E-02
Zelux SD-P	3.54E+04	--
Fluorosint	2.20	2.28E-02

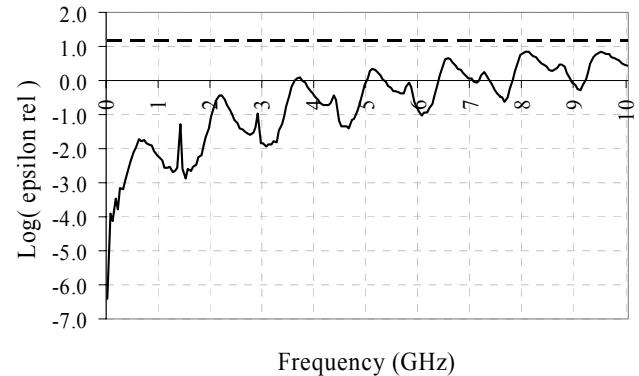


Figure 2. Measured ϵ_r (solid) from 100 MHz to 10 GHz compared to vendor data at 1 MHz (dashed) for *Dolphon*.

A second case is given in figure 3 where $Im(\epsilon)$ is greater than vendor data for the *Fluorosint* material. This figure illustrates a possible failure mode due to resonant absorption of the radiation by the material and subsequent insulator melt down or device failure due to overheating. This illustrates the risks associated with basing system design upon insufficient characterization data at operating points and the fatal impact this can have upon system functionality and viability.

The hockey-puck samples were tested with pulsed HV for dielectric strength and failure, and required a testbed that minimized corona discharge. We note again that this measurement is conducted using pulsed electric fields. Several materials showed the capability for withstanding more than twice the material's dielectric hold-off strength, as rated by the manufacturer. These results, summarized in figure 4, are extremely promising for compacting pulsed power systems due to higher breakdown strength exhibited for pulsed HV. In general, designers use the rule-of-thumb, intuitive estimation of over-volting materials by a factor of two more the benchmarked value.

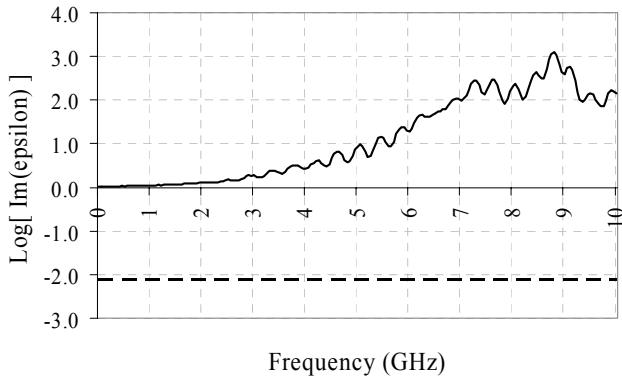


Figure 3. Measured loss (solid) from 100 MHz to 10 GHz compared to vendor data at 1 MHz (dashed) for *Fluorosint*.

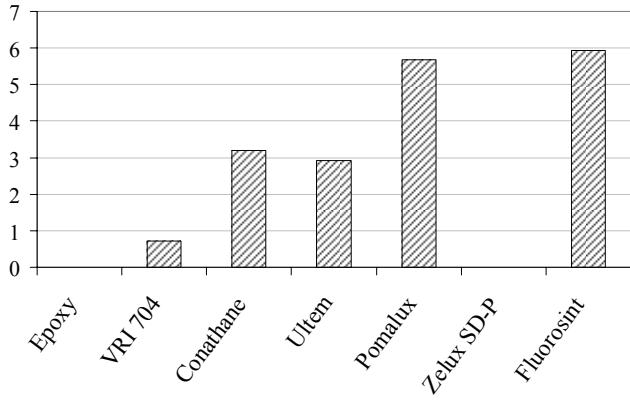


Figure 4. Ratio of vendor dielectric strength to measured dielectric strength.

VI. CONCLUSION

We have demonstrated the need for more extensive characterization of dielectrics used in HV high-frequency applications in the pulse regime. With engineering designs built around vendor specs at 60 Hz and 1 MHz, material specifications are unsatisfactory for design and unable to accurately predict device performance or lifetime for pulsed high frequency HV.

Table 3. Partial discharge and sample voltages, dielectric strength.

Material	Marx charge voltage (kV)		Sample voltage (kV)		Dielectric Strength (V/mil)	
	$V_{\text{partial discharge}}$	$V_{\text{breakdown}}$	$V_{\text{partial discharge}}$	$V_{\text{breakdown}}$	measured	vendor spec
Epoxy 815c/3140	<i>none</i>	37	<i>none</i>	266.4	2664	--
VRI 70	23	27	165.6	194.4	1944	2692.4
Conathane	22	27	158.4	194.4	1944	609.6
Ultem 1000	29	33	208.8	237.6	2376	812.8
Pomalux	30	32	216	230.4	2304	406.4
Zelux SD-P	17	20	122.4	144	1440	--
Fluorosint	22	23	158.4	165.6	1656	279.4

With the advent of HPM devices in remote locations, e.g. satellite, insulation punch through and subsequent device failure become intolerable and thus drive the need for more extensive testing of microwave insulating materials.

Moreover, with discrepancies for loss at high frequency, we must consider the energy absorbed by insulating material and the thermal implications on system design. Loss correlates to the conduction current density which determines the power that is dissipated as heat. A high degree of heating for a system that is repeatedly fired at a high rate forces consideration of the material's temperature as a function of operation time and repetition rate. Material resonances lead to resonant absorption, hence material characteristics should be matched to operational frequency range. An insulator with high loss characteristics that is used in high repetition rate operations at higher frequencies necessarily requires a design which includes an ancillary system to provide cooling.

It is apparent that insulation used in HPM and HE systems requires characterization over the entire functional range, e.g. DC to e.g. 10 GHz. With this provision, we are specifically targeting integration of dielectric materials into existing HV pulsed power supplies with primary emphasis placed on building systems compact enough for mobile deployment.

VII. ACKNOWLEDGEMENTS

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